BEAM DIAGNOSTICS OF THE LIPAC INJECTOR WITH A FOCUS ON THE ALGORITHM DEVELOPED FOR EMITTANCE DATA ANALYSIS OF HIGH BACKGROUND INCLUDING SPECIES FRACTION CALCULATION

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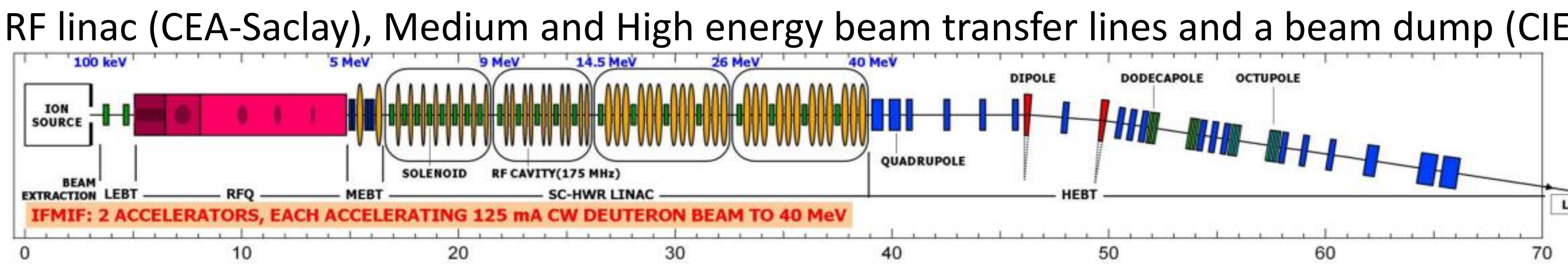
Abstract

To prove the technical feasibility of the IFMIF accelerators concept, the EVEDA phase will commission in Japan the LIPAC accelerator, which will deliver a 125 mA/9 MeV CW deuteron beam. LEDA already managed 100 mA in CW at 6.7 MeV in 2000. The different subsystems of LIPAC have been designed and constructed mainly by European labs with the injector developed by CEA-Saclay. This injector must deliver a 140 mA/100 keV CW deuteron beam at 99% D^+ ratio, which is produced by a 2.45 GHz ECR ion source. The low energy beam transport line (LEBT) is based on a dual solenoid focusing system to transport the beam and to match it into the RFQ. The normalized RMS target emittance at the RFQ entrance has to be within 0.25π mm·mrad. This article describes the diagnostics installed in the LEBT to measure beam parameters such as intensity, profile, emittance, species fraction and degree of space charge compensation. The article also focuses on the algorithm developed to analyze emittance data of high background from an Allison scanner. Species fractions (D^+, D_2^+, D_3^+) using mass separation technique were also calculated during the on-going commissioning campaign with the Allison scanner installed between the two solenoids in a first stage.

Introduction

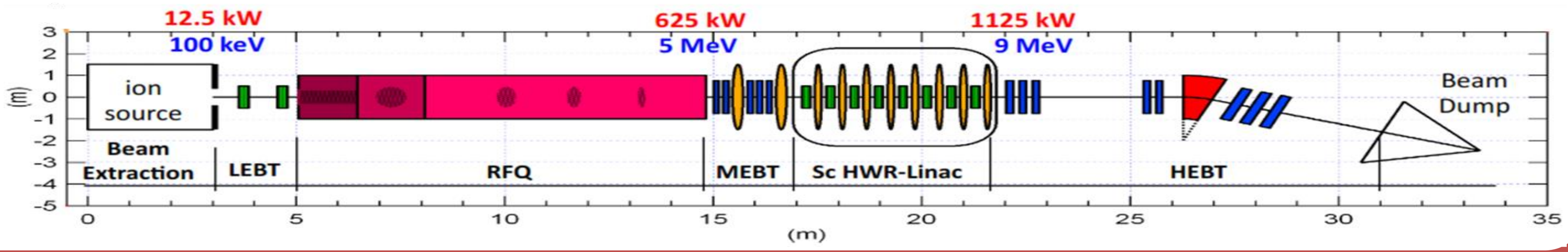
International Fusion Materials Irradiation Facility (IFMIF) project

- ✓ ***Objective:*** Generation of a neutron source with a flux of 10^{18} $m^{-2}s^{-1}$ and a broad peak at 14 MeV in order to characterize and study candidate materials for future fusion reactors
- ✓ ***Principle:*** 2 parallel deuteron accelerators of 5 MW each delivering a high intensity D^+ beam of 2 x 125 mA CW (Continous Wave) at 40 MeV against a liquid lithium target
- ✓ ***LIPAc:*** A 125 mA/9 MeV CW D^+ prototype is commissioned and will be operated in Rokkasho
- ✓ ***LIPAc structure:*** Composed of a deuton injector (CEA-Saclay), a RFQ (INFN), a Superconducting RF linac (CEA-Saclay), Medium and High energy beam transfer lines and a beam dump (CIEMAT)



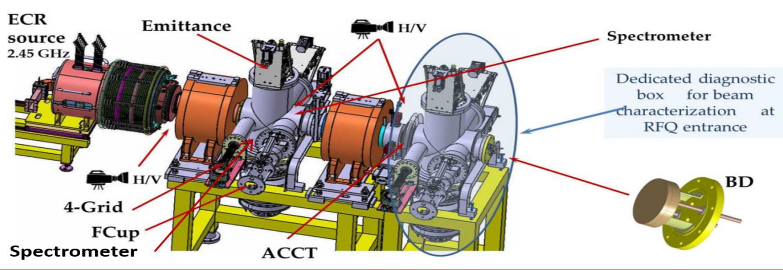
Injector of LIPAc

- ✓ ***Injector structure:*** Composed of the 2.45 GHz ECR ion source based on the CEA-Saclay SILHI source design and a LEBT line that will transport and match the beam into the RFQ
- ✓ ***Current status:*** After acceptance tests performed at CEA-Saclay, it has been shipped to Japan in 2013 and is currently under commissioning in Rokkasho
- ✓ ***Objective:*** Generation of a 140mA /100 keV CW D^+ beam with a normalized RMS emittance lower than 0.30π mm·mrad (with a target value of 0.25π mm·mrad) to ensure <10% losses



Beam Diagnostics in the LEBT

- ✓ ***LEBT structure:*** Consists of an accelerator column, 2 solenoids with integrated H/V steerers, a diagnostic box located between the solenoids and an injection cone located upstream the RFQ
- ✓ ***Injector commissioning:*** A specific diagnostic box, equipped with a beam stopper designed to handle a 15 kW beam, is placed after the injection cone



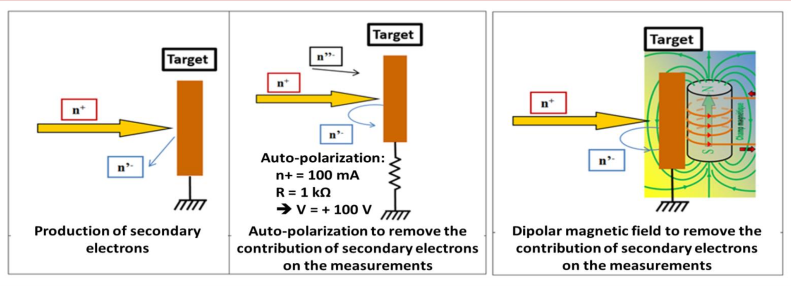
- ✓ ***High beam space charge:*** To minimize the emittance growth, LEBT length minimized to 2.05 m
  ➔ Only necessary diagnostics have been installed to characterize the beam during commissioning and operation

Beam Current Measurement

- ✓ ***Total current extracted from the ECR source:*** Provided with an error of a few percent by the output current flow of the main high-voltage power supply
- ✓ ***Between the two solenoids:*** Current estimated by a movable beam stopper which is initially used to protect the valve isolating the LEBT vacuum from the rest of the system
- ✓ ***At the end of the LEBT:*** Can be measured with an ACCT (AC Current Transformer) located at the end of the injection cone and with the beam stopper located inside the diagnostic box
- ✓ ***ACCT***: Capable of measuring pulsed beams >> few µs, will allow estimating the current transmission of the RFQ by comparison with another ACCT located at the beginning of the MEBT

Improvement of Beam Stoppers Measurements

- ✓ ***Issue with secondary electrons:*** Produced by the interaction of charged particles with a beam stopper in high intensity and low energy beam lines (few tens of eV to 100 eV)
  - Large overestimations of the beam current measurements
  - Partly solved in LIPAc injector by an auto-polarization of the beam stopper

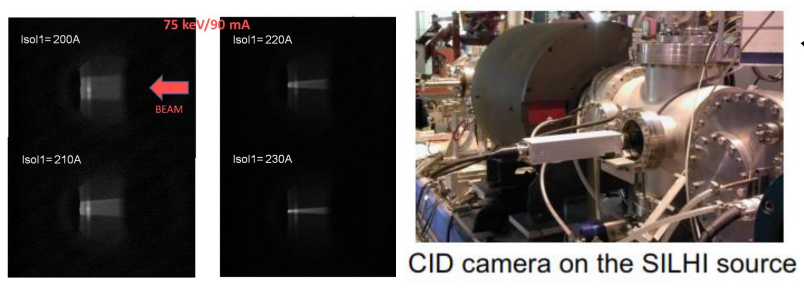


- ✓ ***Auto-polarization:*** Induces the attraction of electrons trapped into the beam (in turn, allowing space charge compensation) and of secondary electrons emitted by the beam hitting the beam pipe
  - Can underestimate the beam current measurements
  - ➔ Study of a dynamic dipolar magnetic system planned to be done

Optical Beam Diagnostics

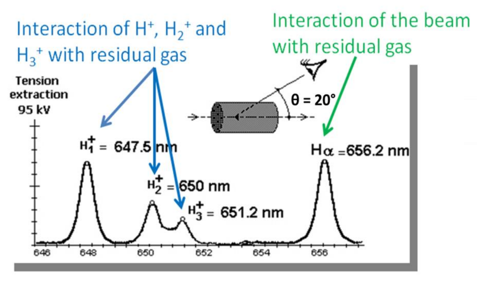
Non interceptive optical beam diagnostics based on the fluorescence of residual gas when the beam passes through it (excitation and de-excitation of the gas molecules)

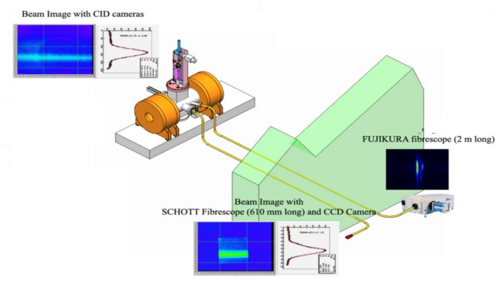
- ✓ ***With CID cameras (Hardened radiations ~ 30 kGy)***
  - Beam current proportional to fluorescence intensity
  - Beam size, beam center position, transverse profile
  - Drawback: low resolution and low sensitivity to light
  - ➔ Installation soon of CDD cameras for proton operation



CID camera on the SILHI source

- ✓ ***With FUJIKURA fibrescope (Hardened) + Monochromator (Doppler Shift) + CCD***
  - Species fraction ratio
  - Species fraction beam profile
  - Source impurities





Results of species fraction measurements from the commissioning at Rokkasho have been reported (K. Shinto et al, Proc. ICIS 2015, C151669-ThuPS18, New-York, Rev. Sci. Instrum. (2016))

Measurement of Space Charge Compensation

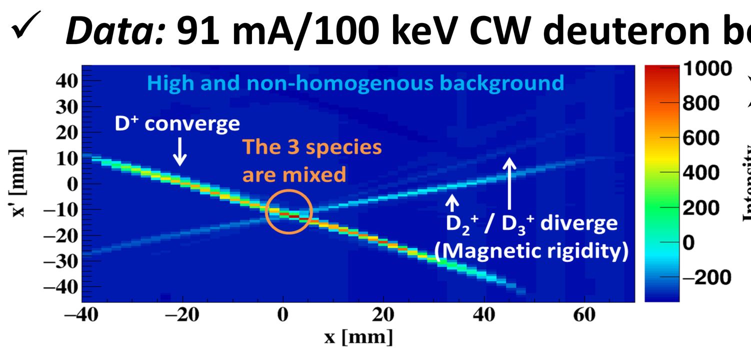
- ✓ ***High beam space charge of LIPAc due to the low energy and high intensity beam:*** Can be partially compensated in the LEBT when the beam interacts with the residual gas of D_2
- ✓ ***Four Grid Analyser:*** Installed in the first diagnostic chamber of LEBT to measure the potential well of the compensated beam, and to calculate the degree of space charge compensation
- ✓ ***Gas injection:*** During deuteron operation at Rokkasho, measurements of space charge compensation and of beam emittance performed with and without Krypton gas injected inside the LEBT *(Y. Okumura et al, Proc. ICIS 2015, WEDM04, New-York, Rev. Sci. Instrum. (2016))*
  - ➔ Space charge compensation and beam emittance have been improved

Emittance data analysis

- ✓ ***Allison scanner:*** Used to measure the vertical emittance in the LEBT of LIPAc
- ✓ ***Design:*** Optimized to sustain 15 kW of beam power in CW and for a critical beam ø of 30 mm
- ✓ ***Ion species:*** ECR source produces not only D^+ but also D_2^+ and D_3^+ molecular ions, with D^+ fraction ratio which should be of at least 80% with a suitable optimization of the source parameters

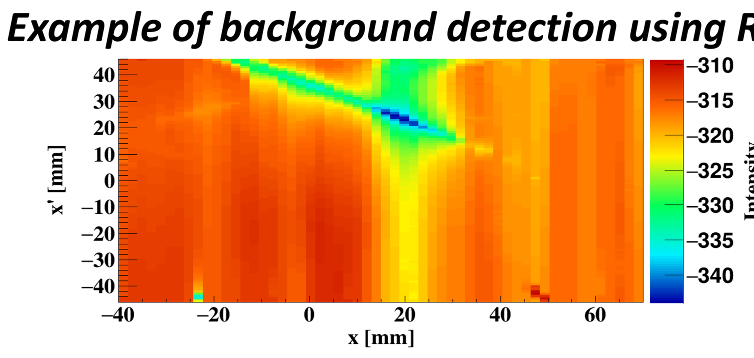
First commissioning stage: Allison scanner between the solenoids ➔ 3 species thus still significantly present (Cone just upstream the RFQ: intercepts D_2^+ and D_3^+ which diverge)

- ✓ ***Data: 91 mA/100 keV CW deuteron beam (2 solenoids set to maximize beam current to RFQ)***



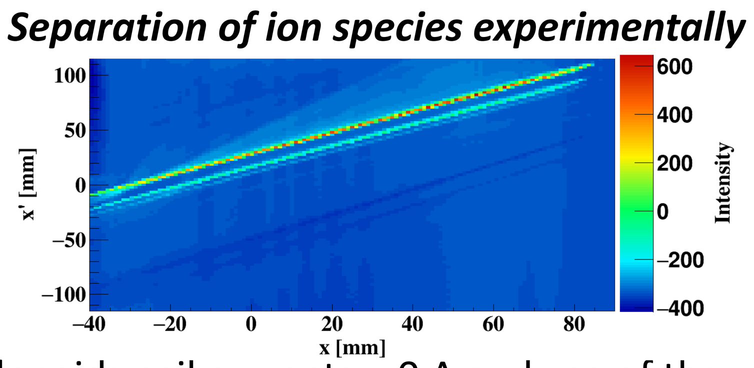
- ➢ ***Data analysis to calculate the emittance of D^+:***
  - Detection and removal of the background
  - Detection of D^+, D_2^+, D_3^+: peaks detection using ROOT
  - D_2^+ / D_3^+ interpolation where the 3 species are mixed
  - Subtraction of this interpolation to D^+ spectrum
- Species fraction ratio also obtained by calculating the integrated intensity of each isolated species
- Algorithm developed to perform these different steps automatically for the beam tuning
- Species fraction ratios measured with the Allison Scanner and the spectrometer were compared *(K. Shinto et al, Proc. ICIS 2015, C151669-ThuPS18, New-York, Rev. Sci. Instrum. (2016))*

- ✓ ***Example of background detection using ROOT***



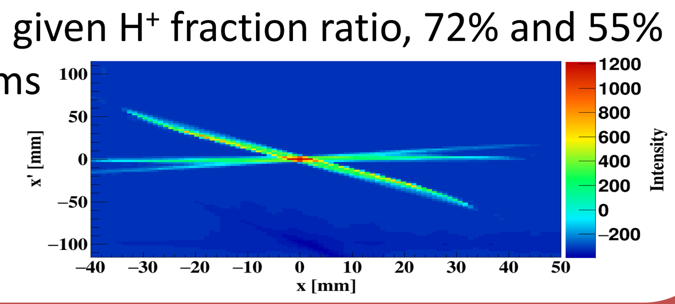
- Negative signal homothetic to the beam: probably due to secondary electrons produced inside the Allison scanner
- Neutral particles at X-position = 20 mm

- ✓ ***Separation of ion species experimentally***



- Solenoids coil currents = 0 A and use of the steerer integrated in the 1st solenoid
- Emittance / H^+ fraction values: < 1% difference compared to the use of solenoids with no steerer

- ✓ ***Algorithm efficiency:*** Simulations performed between solenoids with a 170 mA/50 keV proton beam for a normalized RMS emittance of 0.45π mm·mrad and for 2 given H^+ fraction ratio, 72% and 55%
  - Background detected with ROOT from arbitrary real measurements were first multiplied by a fixed factor and then added to the simulated emittance histograms
  - The algorithm was used to calculate the emittance of the H^+ beam and the H^+ fraction ratio from these noisy simulations
  - Results were compared with the ones given by simulations (before adding background) and differences from less than 1% to a maximum of 4% were observed
  - ➔ This shows that the background is accurately removed and that the interpolation accuracy is sufficient with this algorithm



Conclusion

Beam diagnostics of the LIPAc injector have been commissioned at Rokkasho and are indispensable tools to achieve the required challenging beam characteristics at the RFQ entrance to allow CW operational mode. Modifications to enhance performance are planned such as the installation of a dipolar magnetic system to get a more accurate measurement of the beam current with the beam stoppers and the installation of CCD cameras during proton beam commissioning. In order to analyse raw emittance data of high and non-homogenous background from an Allison scanner, an algorithm has been developed that allows both an automatic on-line calculation of the emittance rms values and of the species fraction ratio.

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